Quantum computing at underground facilities

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Snowmass CPM

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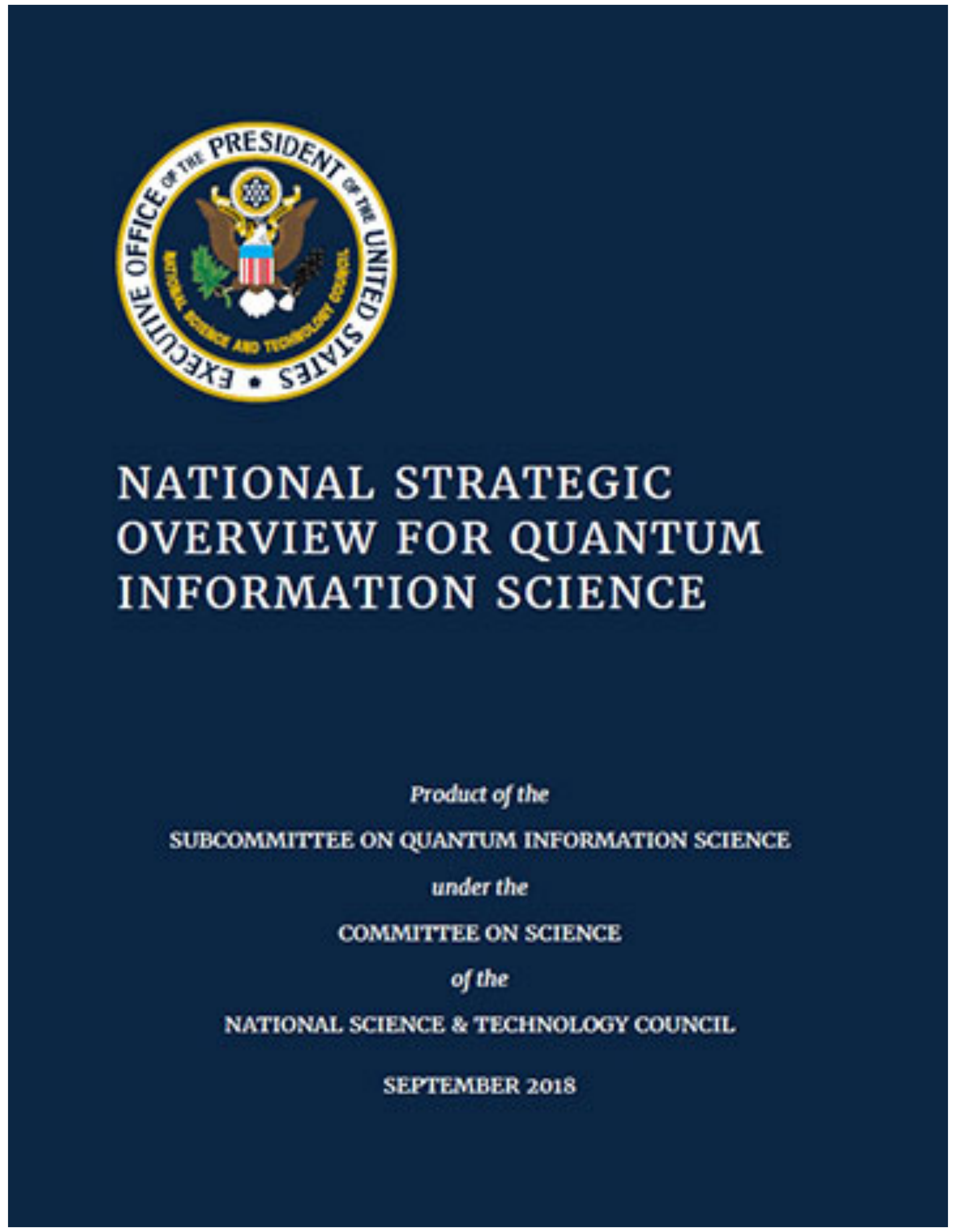
QIS - the “big picture” for the HEP Researcher

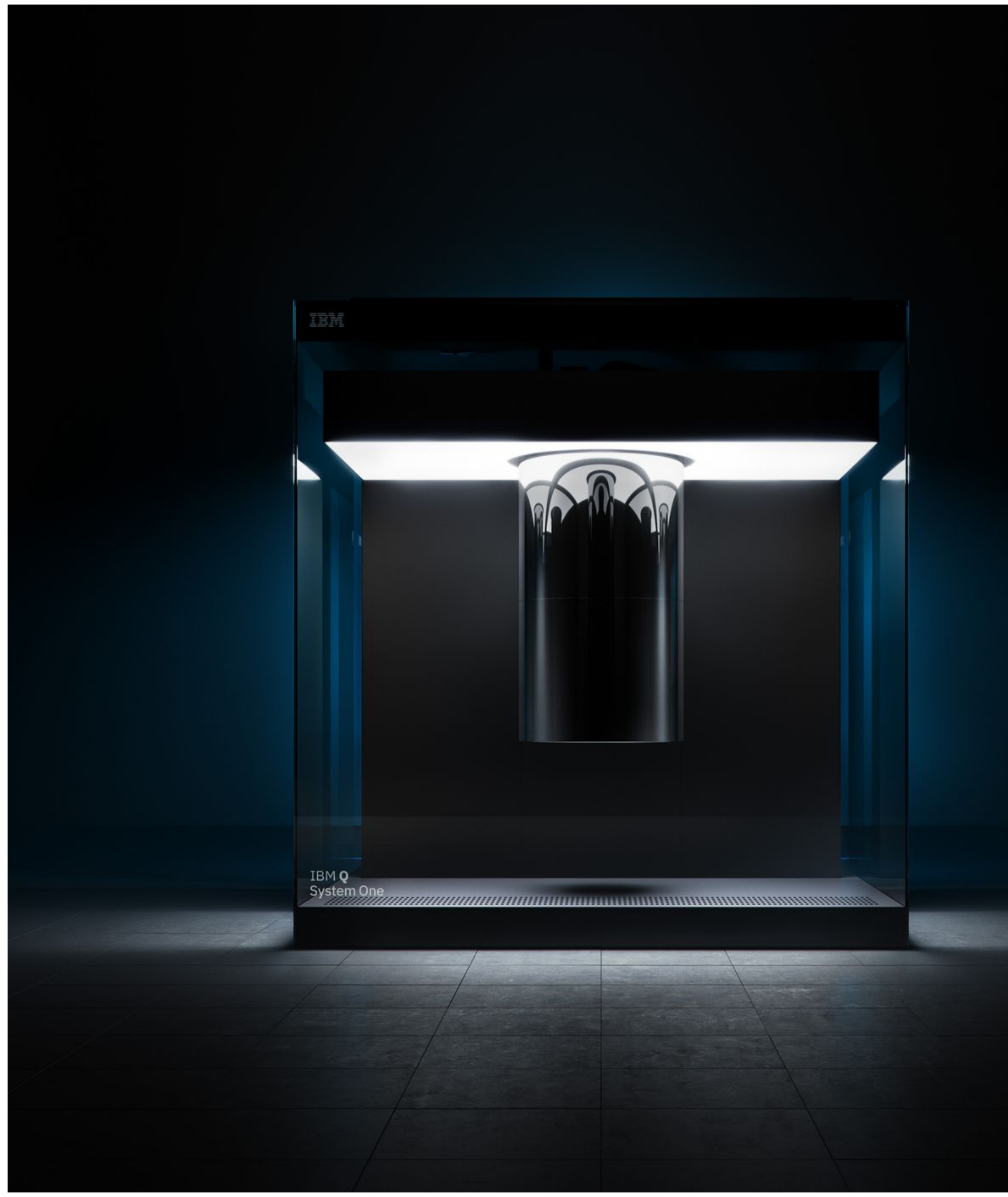
- Quantum technology has the potential to address physics questions we care deeply about that we may not be able to access any other way.
- HEP has a number of world-leading science and technology capabilities that have grown out of our accelerator-based science program that enables our community to deliver important advances for quantum information science on the societal scale.
- There are significant "new money" funding opportunities in quantum information science -> pursuing quantum science will not "cannibalize" the rest of our program.
- We are already making significant progress on all three of the above points, but as quantum information is "organizationally new" (if not scientifically new) to HEP, it is important that we organize a coherent "full-stack" plan quickly or we may lose out on a significant set of scientific opportunities.



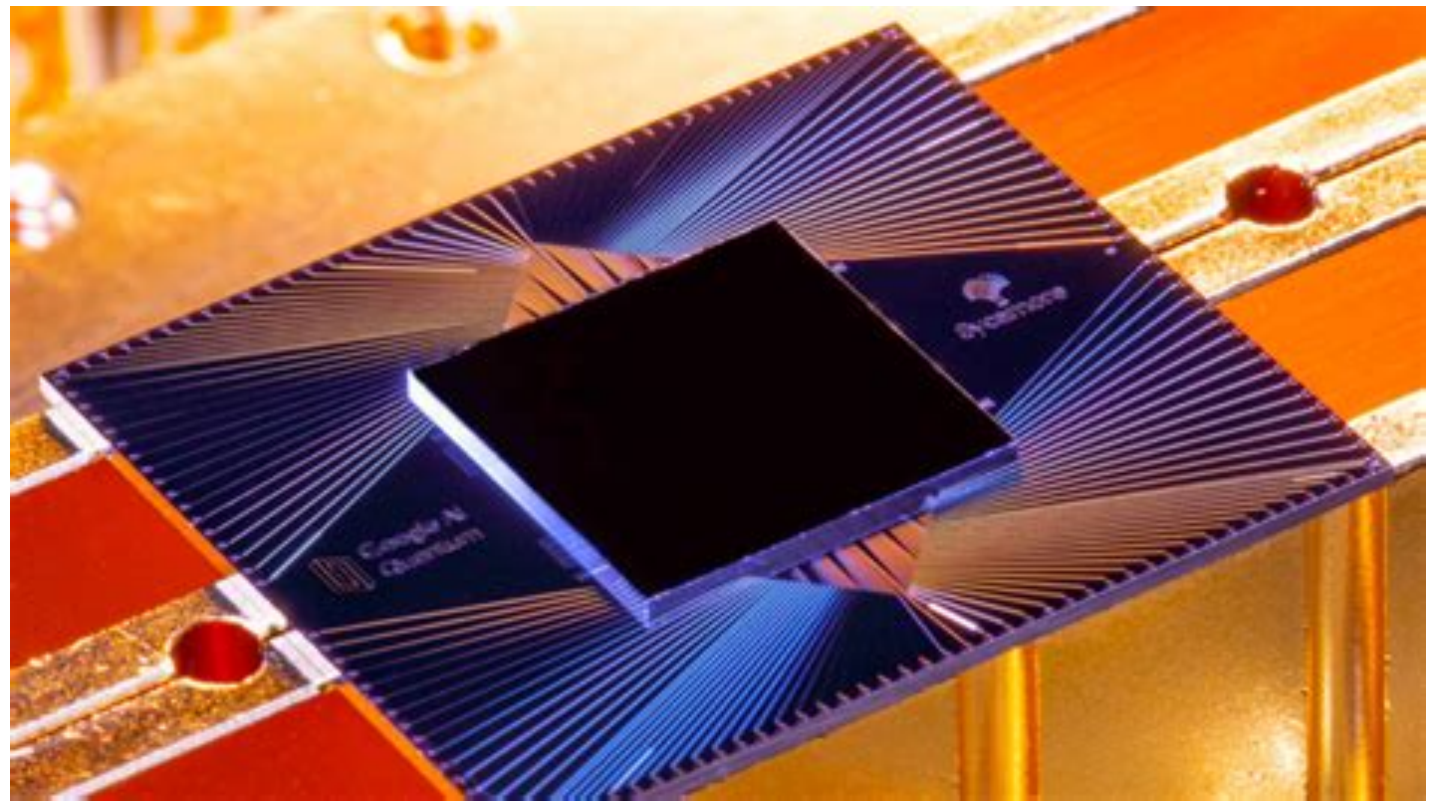
QIS for the underground

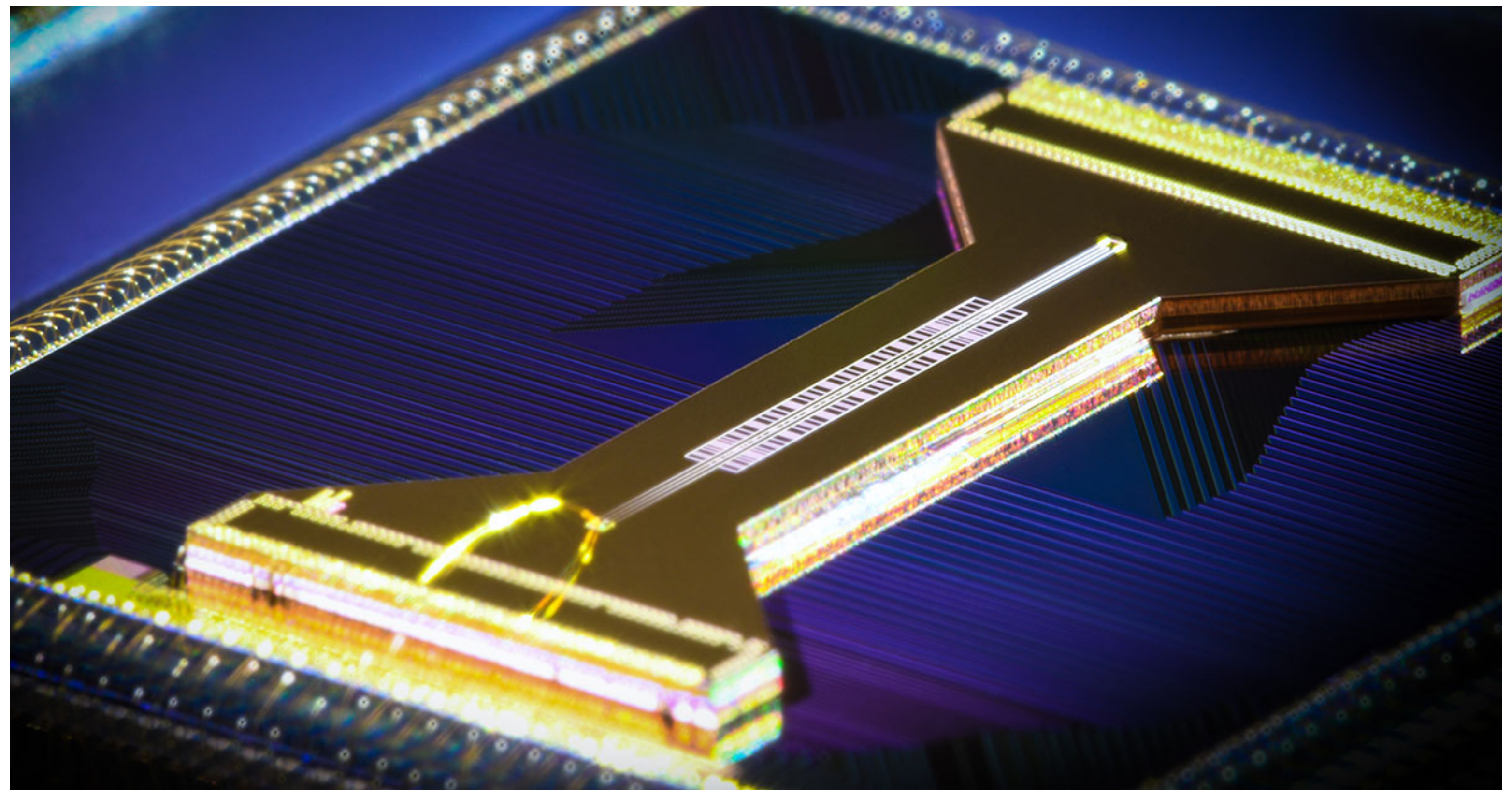
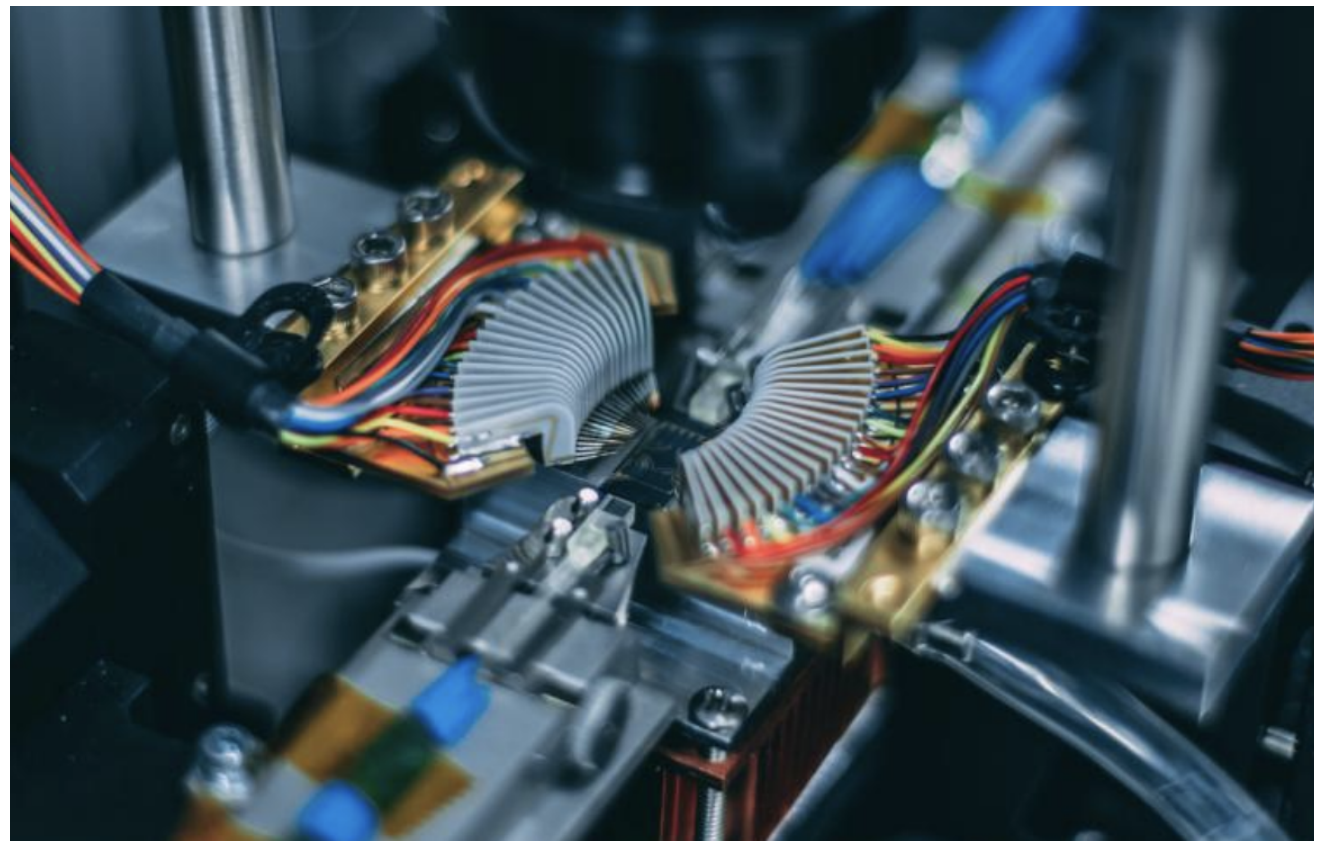
- Underground facilities provide a number of wonderful advantages for quantum sensing experiments. This is well-recognized (and many current efforts using quantum technologies aren't even using that "branding").
- An application that is not widely considered though is ***quantum computing***.
- ***Quantum technology is distinguished by leveraging entanglement and superposition of quantum states.*** In quantum computing, we leverage these aspects of quantum mechanics to perform certain calculations more efficiently than can be done with von Neumann architectures. While there are currently only a few algorithms with proven quantum "advantage", they are versatile and have many applications.

Underground quantum computing, continued



- Quantum computing is limited by several factors, but one of the most important is ***decoherence errors***. Recent research suggests one source of decoherence errors is ***cosmic rays***.
- Some quantum architectures are more sensitive to this than others (for example, superconducting transmon qubits present a larger surface cross section than ion trap-based machines). It is a topic of open research to understand these sensitivities and how they apply to different quantum computing technology implementations.



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Studies on superconducting qubits

- Superconducting transmon qubits are the current technological leaders (some controversy here - but they are the most publicly available and have the most demonstration results today).
- Recent study in Nature* highlighted the impact of ionizing radiation on qubit coherence.

Impact of ionizing radiation on superconducting qubit coherence

Antti P. Vepsäläinen, Amir H. Karamlou, John L. Orrell, Akshunna S. Dogra, Ben Loer, Francisca Vasconcelos, David K. Kim, Alexander J. Melville, Bethany M. Niedzielski, Jonilyn L. Yoder, Simon Gustavsson, Joseph A. Formaggio, Brent A. VanDevender & William D. Oliver

*https://www.nature.com/articles/s41586-020-2619-8

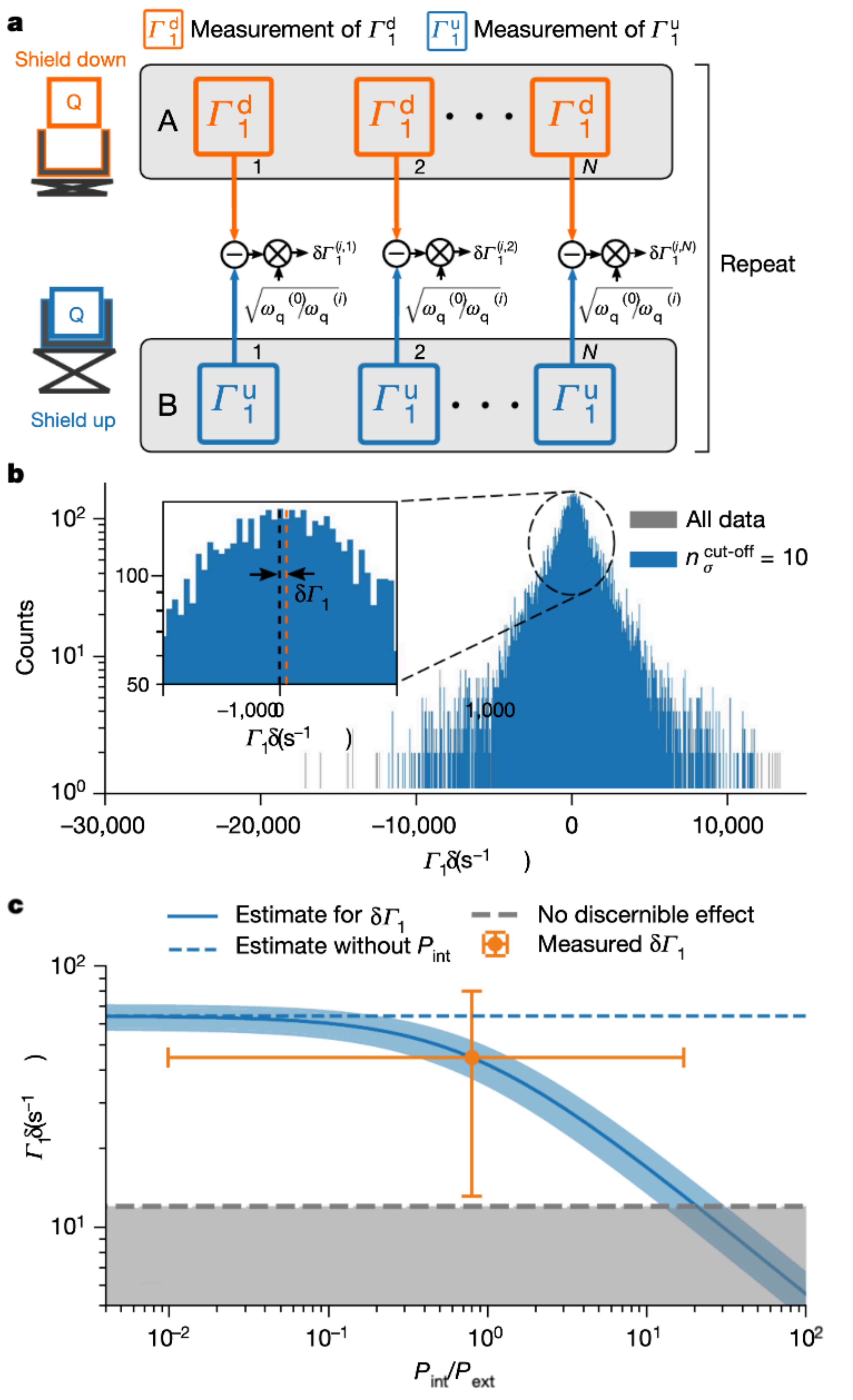

Fig. 4 | Qubit shielding experiment. a, Schematic of shielding experiment. The qubit energy-relaxation rate is measured *N* times with the shield up and then again *N* times with the shield down. This cycle is repeated 65 times for qubits Q1 and Q2, and 85 times for qubits Q3–Q7. **b**, Histogram of the differences in energy-relaxation rates when the shield is up versus down. The inset shows the histogram peak. The orange vertical line indicates the median of the distribution. Although the median difference in the relaxation rates between shield-up and shield-down configurations is only 1.8% of the width of the distribution, it differs from zero in a statistically significant manner. **c**, Difference in the energy-relaxation rates in the shielding experiment (orange dot) versus P_{int}/P_{ext}. Vertical error bars show the 95% CI for the median of $\delta\Gamma_1$. Horizontal error bars are the corresponding CIs for P_{int}. The blue line indicates the energy-relaxation rate estimated using the model from the ^{64}Cu radiation exposure measurement and equation (6). The shaded blue region shows the CI for the estimate, assuming ±20% relative error for P_{ext}. Below the grey dashed line, the experiment is not sensitive enough to detect $\delta\Gamma_1$.

Studies on superconducting qubits, continued

Discussion

The first reported results of the systematic operation of superconducting transmon qubits under intentionally elevated levels of ionizing radiation clearly show a deleterious effect on the performance of the qubits. We quantitatively determined the impact of radiation power density on the qubit energy-relaxation time and showed that naturally occurring ionizing radiation in the laboratory creates excess quasiparticles in superconductors, reducing the qubit energy-relaxation time.

By using shielding techniques commonly applied in neutrino physics and the search for dark matter[33–39], we improved the energy-relaxation rate of our qubits by approximately 0.2%. Although a rather small improvement for today's qubits, which are currently limited by other relaxation mechanisms, a simple model of the ionization generation of quasiparticles indicates that transmon qubits of this design will need to be shielded against ionizing radiation—or otherwise redesigned to mitigate the impact of its resulting quasiparticles—to reach energy-relaxation times in the millisecond regime. Additionally, as was recently done with resonators[19], locating qubit systems deep underground where cosmic rays and cosmogenic activation are greatly reduced should provide benefits for advancing quantum computing research.

Impact of ionizing radiation on superconducting qubit coherence

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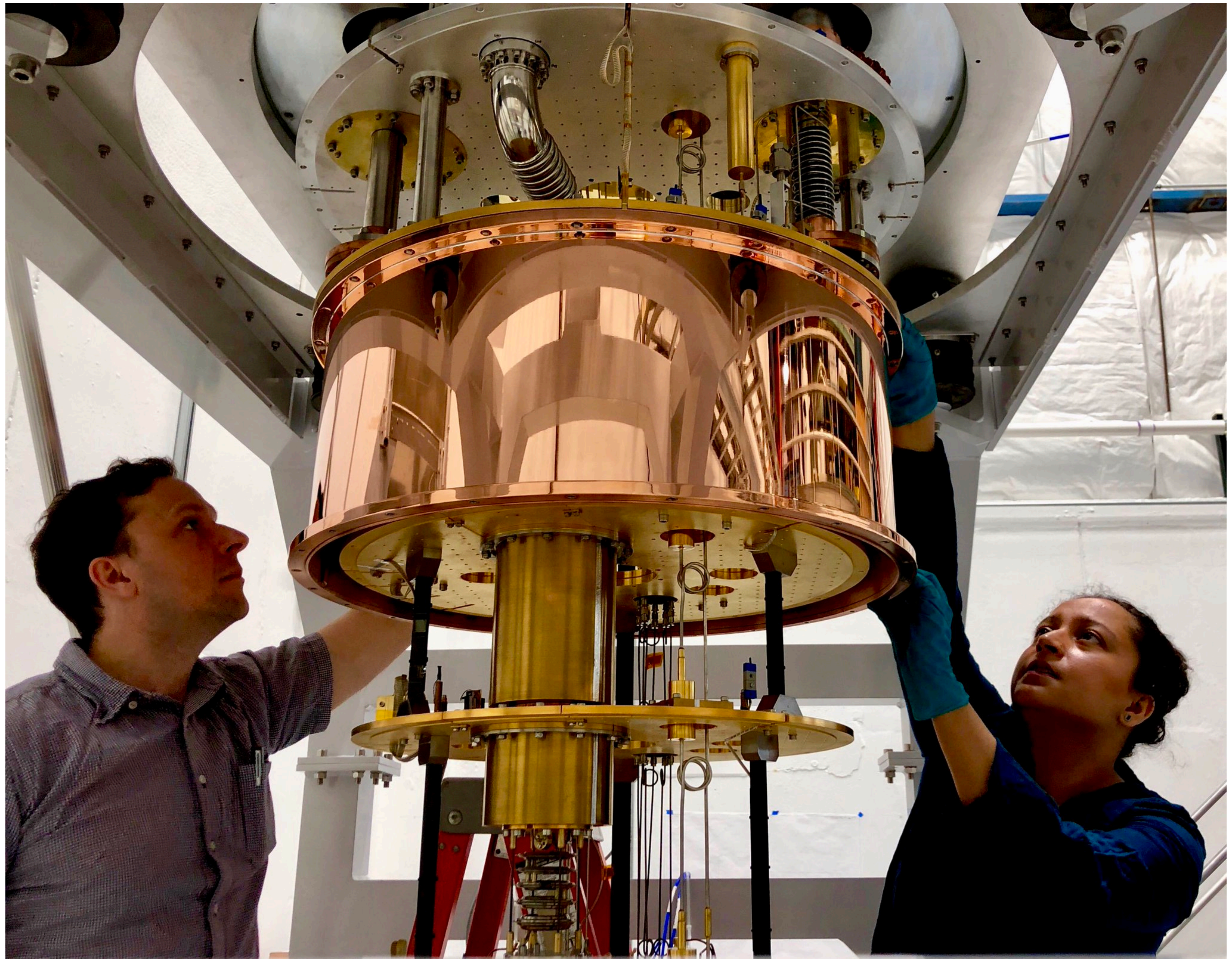
Underground facilities

- Wide range of possible outcomes.
  - Research capabilities on the scale of ~a few dilution refrigerators seem like an excellent investment.
    - Could likely attract industry partnerships to help finance the infrastructure.
    - Dual-use for sensing experiments makes this a low-risk investment.
  - Depending on the overall impact, it is even possible industry leaders would want to build “quantum data centers” underground.
    - It wouldn’t be the first cloud data center stored in a novel location…

https://news.microsoft.com/features/under-the-sea-microsoft-tests-a-datacenter-thats-quick-to-deploy-could-provide-internet-connectivity-for-years/



D. Bowring and R. Khatiwada prepare a dilution refrigerator for service at Fermilab.